

Research on the Coupling Mechanism of Multi-Hazards and the "Five-in-One" Collaborative Prevention and Control Technology in the Syncline Axis Working Face

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Abstract

The syncline axis area, influenced by the convergence of water in structurally low-lying zones, enhanced formation sealing properties, and the superimposed effects of stress concentration and mining disturbance, is prone to the co-enrichment and chain amplification of multiple hazards within the same region, including water disasters, fires, goaf hazards, and toxic and harmful gases such as gas and hydrogen sulfide. Based on the 9401 working face of Hengsheng Coal Industry, this study integrates structural control, mining-induced fracture evolution, and the reconstruction characteristics of seepage and ventilation flow fields to reveal the coupling mechanism of multi-hazards in the syncline axis. A "Five-in-One" closed-loop collaborative prevention and control system, encompassing "Prediction-Early Warning-Precontrol-Prevention and Control-Collaboration," has been established. Field applications demonstrate that during the mining process through the syncline axis, the gas environment in the goaf remained stable, water inflow was relatively low, and the impact of toxic and harmful gases was minimal, ensuring safe extraction in the complex section of the syncline axis.

Keywords

Syncline Axis; Multi-Hazard Coupling; Tube Bundle Monitoring; Collaborative Prevention and Control.

1. Introduction

The syncline axis area, affected by the superposition of structural stress concentration and mining disturbance, easily induces the spatiotemporal coupling and chain amplification of multiple hazards such as water, fire, gas, and hydrogen sulfide [1- 3]. Existing research mostly focuses on the evolution mechanism and monitoring technologies of single hazards, achieving fruitful results in water control, fire prevention, and gas governance [4- 7]. However, in strongly coupled scenarios like the syncline axis, the mechanisms of "mutual induction and reinforcement" among hazards remain unclear, and traditional single-hazard, sub-system governance models struggle to meet the demands of whole-process collaborative control. Therefore, this paper takes the 9401 working face of Hengsheng Coal Industry as the engineering background to analyze the "water-gas-heat-structure" multi-hazard coupling mechanism in the syncline axis. A "Five-in-One" closed-loop prevention and control system of "Prediction-Early Warning-Precontrol-Prevention and Control-Collaboration" is constructed, aiming to provide theoretical and engineering support for safe and efficient mining in complex structural sections.

2. Engineering Background

The 9401 working face of Hengsheng Coal Industry, located in the west of the No. 4 mining area, is 1086 m long and 239 m wide, with an average coal seam thickness of 6.1 m and a dip angle of 7°. Controlled by the Liujiashuang syncline axis, the working face area exhibits significant abnormal emissions of methane and hydrogen sulfide (H₂S) as well as enhanced water inflow. Additionally, mining-induced fractures and water exploration boreholes can easily connect the overlying No. 2 coal seam goaf with surface fissures, forming compound air leakage channels that increase the risk of spontaneous combustion. Consequently, the 9401 working face faces the severe challenge of the spatiotemporal superposition and mutual coupling of water, fire, gas, and toxic gas disasters during mining.

3. Analysis of Multi-hazard Mutual Induction Mechanism

Under the combined influence of structural stress concentration and mining disturbance, the syncline axis of the 9401 working face exhibits significant enrichment and chain amplification of water, fire, gas (CH₄, H₂S), and goaf disasters. The mutual induction mechanisms are as follows:

Water-Gas-Heat Multi-Field Coupling: Water migration triggers the "water-driving-gas" effect, accelerating the desorption of adsorbed CH₄ and dissolved H₂S. Residual coal oxidation and temperature rise exponentially promote gas emission, while seepage expands air leakage channels and oxidation zones, leading to the dynamic conversion of water and fire risks.

Goaf Structure Evolution Control: Mining-induced instability and subsidence create composite spaces for water accumulation and gas enrichment. This not only destroys sealing facilities but also reconstructs the flow field, promoting the cross-regional migration of harmful gases and oxygen intrusion, thereby exacerbating chain reactions.

Structural Stress Amplification: The high-stress environment at the axis promotes fracture connectivity, providing advantageous channels for fluid migration. The unloading effect in the stress peak zone is prone to inducing instantaneous gas outbursts.

Consequently, a "water-fire-gas-goaf-structural stress" five-element dynamic disaster system is formed, necessitating a collaborative strategy of multi-element integration and full-cycle control.

4. Overall Strategy for Multi-Hazard Prevention and Governance

A "Five-in-One" closed-loop system of "Prediction- Early Warning- Precontrol- Prevention- Collaboration" was constructed to address multi-hazard coupling:

Prediction: Utilize "3D geology-stress-seepage" modeling to precisely characterize hazard boundaries and targets.

Early Warning: Implement multi-source fusion monitoring (gas, water, heat) to shift from post-event alarms to proactive alerts.

Precontrol: Cut off disaster chains at the source through advance grouting, aquifer depressurization, and coal seam alkali injection.

Prevention: Stabilize the mining environment using zonal sealing for air leakage and chemical absorption for H₂S.

Collaboration: Achieve spatial-temporal synergy in governance and emergency response via a comprehensive management platform.

5. Analysis of Multi-Hazard Governance Effects

As shown in Figure 1, continuous observation of water inflow data was conducted during the mining period at the 9401 working face. The statistics began from the point where the working face's machine tunnel came into contact with the syncline axis and continued until the working face successfully

passed through the syncline axis, covering the period from July 3, 2025, to October 9, 2025. The water inflow at the working face was relatively small and within a controllable range (Fig. 1).

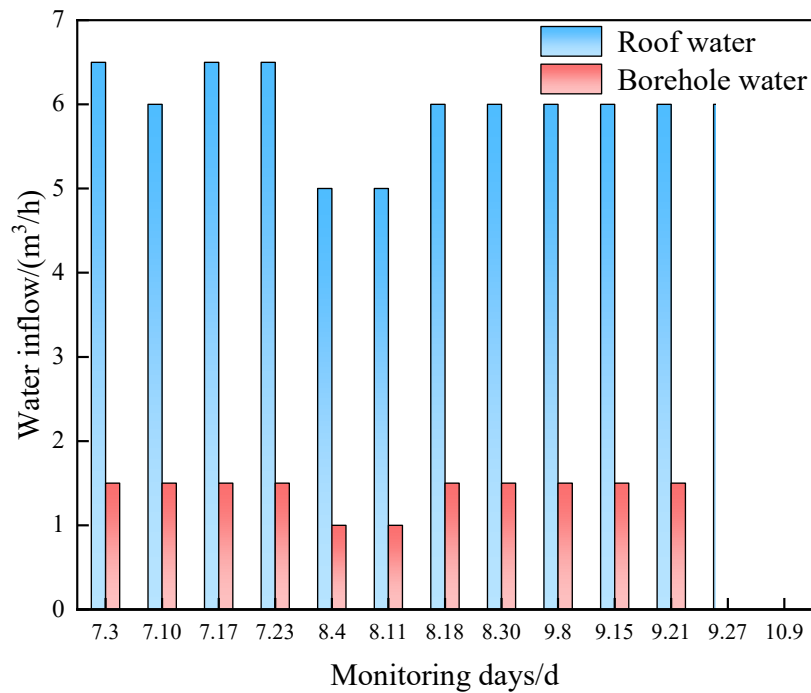


Fig. 1 Water inflow in the 9401 air lane

During the mining of the 9401 working face through the syncline axis (July–October 2025), the application of the collaborative prevention and control system yielded significant results:

Despite structural stress concentration, methane (CH₄) concentrations were consistently controlled below 0.12% and showed a decreasing trend, eliminating overrun risks (Fig. 2).

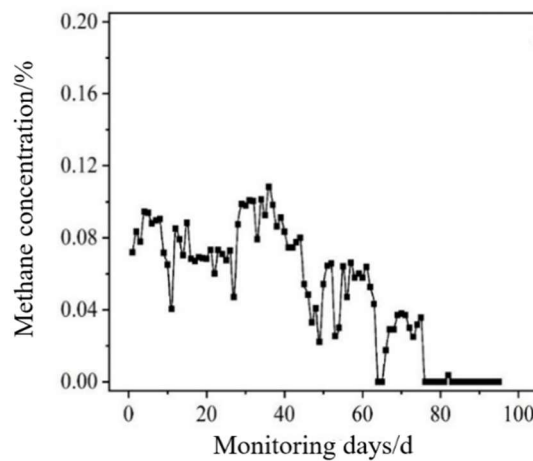


Fig. 2 Gas concentration monitoring curve

H₂S Control Verification: Hydrogen sulfide emissions exhibited significant “structural control” characteristics, initially peaking at 12 ppm due to fracture connectivity. Notably, a distinct concentration rebound observed during a temporary suspension of alkali injection (days 50–60) inversely verified the critical effectiveness of the source chemical neutralization strategy (Fig. 3).

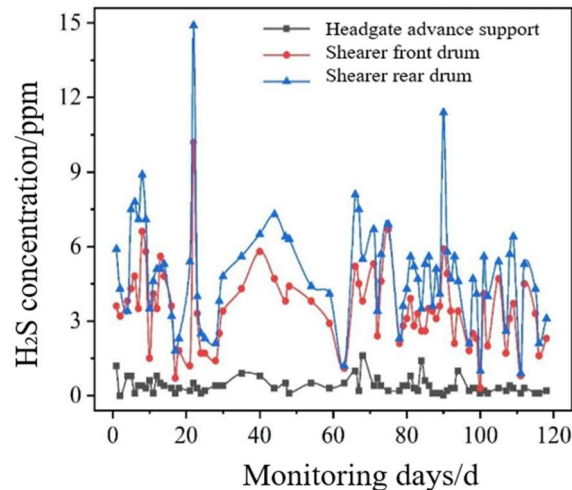


Fig. 3 H₂S monitoring curve

Overall, the system effectively suppressed multi-hazard coupling, ensuring safe mining in the complex structural zone.

6. Conclusion

This study reveals the "water-fire-gas-goaf-structural stress" multi-hazard chain coupling mechanism in the syncline axis and constructs a "Five-in-One" collaborative prevention and control system comprising prediction, early warning, precontrol, prevention, and collaboration. Field application at the 9401 working face verified the system's effectiveness, achieving stable water inflow, maintaining methane concentrations below 0.12%, and effectively controlling hydrogen sulfide (confirmed by concentration rebound during treatment interruption), thereby ensuring safe mining in complex structural zones.

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References

- [1] K.X. Zhang, J.A. Zhu, M.C. He: Mechanical analysis of rock burst and impact characteristics research in mining roadways under syncline action, *Coal Science and Technology*, Vol. 50 (2022) No. 7, p.84-98.
- [2] Z.Y. Wang, J. He: Research on mechanism and prevention and control of coal-rock dynamic disasters in complex geological structure areas, *Safety in Coal Mines*, Vol. 52 (2021) No. 9, p.204-210.
- [3] K.K. Dong, D. Song, H. Yao: Research on application of composite support method for mudstone roadway in syncline axis with large burial depth, *China Energy and Environmental Protection*, Vol. 43 (2021) No. 5, p.258-262.
- [4] Y.P. Miao, X.H. Zheng, K. Liu: Intelligent early warning and prevention technology and application for multi-hazards in coal mines, *Intelligent Mine*, Vol. 4 (2023) No. 6, p.71-78.
- [5] W.X. Long, F.L. Meng, X. Li: Research on division technology of spontaneous combustion danger zone in 1802 working face of Xinzhuang Coal Mine, *Inner Mongolia Coal Economy*, 2025, No. 14.
- [6] C. Liu, G. Huang, Z.L. Song: Experimental study on effect of hydrostatic pressure on raw coal gas desorption, *Chinese Journal of Rock Mechanics and Engineering*, Vol. 35 (2016) No. 9, p.1837-1843.
- [7] X.M. Hu, H.B. Hong, H. Dong: Application research on "Radon-Magnetic" method for detecting spontaneous combustion in small coal mines, *Coal Science and Technology*, Vol. 53 (2025) No. 2, p.200-210.